GOATS'2002
Multi-static Active Acoustics in Shallow Water

Henrik Schmidt
John Leonard
Department of Ocean Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
Phone: (617) 253-5727 Fax: (617) 253-2350 E-mail: henrik@keel.mit.edu

Award #: N00014-97-1-0202
http://acoustics.mit.edu/arctic0/henrik/www/home.html

LONG-TERM GOAL

Develop environmentally adaptive bi- and multi-static sonar concepts for autonomous underwater vehicle networks for detection and classification of proud and buried targets in very shallow water.

OBJECTIVES

The objective of the ocean acoustics components of the GOATS project is to develop a fundamental understanding of the 3D mid-frequency (1-20 kHz) acoustic environment associated with the mine countermeasures (MCM) problem in shallow water (SW) and very shallow water (VSW) and to develop efficient physics based propagation and scattering models incorporating aspect-dependent targets and seabed features, and the waveguide multipath effects. The goal is a consistent physics-based modeling framework for high-fidelity simulation of bi-and multistatic sonar configurations for VSW MCM which may form the basis for new acoustic classification techniques based on spatial and temporal target resonance characteristics. Specific scientific objectives include the investigation of mechanisms responsible for sub-critical penetration into sediments in the mid-frequency regime (1-20 kHz), the effects of sediment porosity, and the coupling between the structural acoustics of targets and the environmental acoustics of the littoral waveguides.

APPROACH

The development of GOATS (Generic Ocean Array Technology Sonar) is a highly interdisciplinary effort, involving experiments, and theory and model development in advanced acoustics, signal processing, and robotics. The center piece of the research effort is the GOATS'2000 Joint Research Program (JRP) conducted by SACLANTCEN and MIT with ONR support, which was scheduled to finish in Aug. 2001, but which has been extended with 5 years, formally incorporated in the SACLANTCEN Program of Work. Building on the experience of the highly succesful GOATS'98 pilot experiment [2] and the GOATS'2000 [9] experiment, the JRP continues with a series of experiments, with the two major ones being planned for 2002 and 2004, and modeling and simulation work to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of VSW. The modeling effort is centered around the OASES environmental acoustic modeling framework developed at MIT [1,4]. OASES is a widely distributed suite of models covering a variety of ocean waveguide and source/receiver representations.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **GOATS' 2002 Multi-static Active Acoustics in Shallow Water**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Ocean Engineering,,Massachusetts Institute of Technology,,Cambridge,,MA, 02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Develop environmentally adaptive bi- and multi-static sonar concepts for autonomous underwater vehicle networks for detection and classification of proud and buried targets in very shallow water.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Thus, the most recent developments are computational modules for full wave theory modeling of mono-and bistatic reverberation in shallow water waveguides. In collaboration with SACLANTCEN the waveguide reverberation code OASSP has been modify to consistently model the mono- and bistatic reverberation from interface roughness and seabed volume inhomogeneities in azimuthally symmetric sonar scenarios [6]. Another module, OASES-3D provides wave-theory modeling of the full 3-D acoustic environment associated with mono- and bi-static configurations in VSW with aspect-dependent targets and reverberation features [3,4]. OASES-3D incorporates environmental acoustic features specifically associated with bi-static sonar concepts in shallow water, including aspect-dependent target models, seabed porosity, and scattering from anisotropic seabed roughness such as sand ripples. The validation of these models is one of the major objectives of the GOATS JRP with SACLANTCEN.

In addition to the acoustic research, the continuation of GOATS involves a significant effort addressing the fundamental robotics issues associated with the collaborative operation of multiple autonomous underwater vehicles in shallow water, including navigation, inmter-platform acoustic communication, and adaptive, cooperative behavior. Specifically the current effort explores the development of Concurrent Mapping and Localization (CML) algorithms for networks of AQUV-s, and the implementation of efficient inter-vehcle acoustic communication protocols enabling the cooperative behavior which is crucial to the implementation of the GOATS concept.

WORK COMPLETED

GOATS'2002 Experiment

Figure 1: MASAI-02: Caribou Odysssey III AUV ready for launch, with R/V Alliance in background

The main component of the FY02 effort was the planning and execution of the BP-02/MASAI-02 experiments, carried out jointly with SACLANTCEN under the International Cooperation on AUV Technology Joint Research Program. MIT participated in the BP-02 (Battlefield Preparation) Rapid Environmental Assessment (REA) experiment, May 25-June 2, 2002, and the MASAI-02 Multi-AUV Cooperative and Adaptive Detection and Classification of Buried Targets experiment, June 4-June 18, 2002.

Objectives

The objective of the MIT component of BP-02/MASAI-02 was to develop the fundamental technology enabling the use of multiple, cooperating AUV's for autonomous, concurrent detection and classification of proud and buried targets using low-frequency, bottom-penetrating synthetic aperture sonar technology. The main objective of this research is the development SAS processing of sonar signals recorded concurrently by mono- and bi-static apertures, and the associated auto-focusing. Other enabling technology that were be tested and demonstrated are new navigation and communication technology for multiple Autonomous Underwater Vehicles performing cooperative surveys. Specifically the MIT components of BP-02/MASAI-02 attempted to demonstrate the field performance of new Concurrent Mapping and Localization (CML) algorithms currently being developed at MIT. The acoustic communication effort demonstrated inter-vehicle acoustic communication for coordinated seabed surveys using a mono-static synthetic aperture sonar on one ASUV and a video camera on the other. The final objective was to demonstrate autonomous, adaptive vehicle behavior based on real-time onboard processing of sonar data, with one or both vehicles being adaptively redirected based on on-board, conventional and SAS processing. Even though all of these objectives were not met completely, significant progress was made in all areas.

Equipment

The original plan was to deploy three AUV's in BP-02/MASAI-02, with up to two being deployed concurrently for dual-vehicle mission tests, but the second of two new Bluefin Odyssey-III AUVs was not completed in time due to delay in funding. As a result, MIT deployed only two AUVs. The main AUV platform was be a new, modular Odyssey III, Caribou, recently acquired from Bluefin Robotics by MIT. It was operated with two different payload sections, one being an Edgetech combined SSS-SBP sonar, and the other being a SAS sonar system consisting of interchangeable nose-mounted 2x8-element and 1x16-element nose arrays built at SACLANTCEN, and center payload section containing a dedicated data acquisition system and an Edgetech 4-16kHz SSB profiler source used as active element. The source is re-configurable to provide 2-sided, insonification grazing angles in the range 20-90 degrees.

As a second vehicle MIT operated a refurbished Odyssey II, Xanthos. This vehicle was equipped with a video camera. The two vehicles operated the same new vehicle control software, MOOS, currently being developed at MIT. They also operated the same navigation and communication hardware and were therefore interchangeable in regard to all the navigation and communication work planned for MASAI-02.

 

Operation

The AUVs were operated by a team of engineers from Bluefin Robotics and the MIT Sea Grant AUV Laboratory. The main difference in operation procedure from earlier GOATS experiments was the use of the aft bridge of Alliance as operations center for all MIT AUV operations. This was made possible by the new MOOS operating system allowing full remote radio programming and control of the AUVs. In earlier experiments all operations were conducted from MSL, without visual contact with the vehicles, not even on the surface. The use of the aft bridg provided a much more efficient operational environment, and towards the end of the experiment missions could be turned around in very short time, and a total of more than 500 dives were completed by the MIT team during BP-02 and MASAI-02, most of them short, but for the type of AUV research performed by MIT, focusing on the developing the fundamental technology, many short missions in rapid succession is crucial.

The early part of the cruise was hampered by rough seas and windy conditions in Framura, and only one half day of full operations was achieved during the first week of MASAI-02, June 4. SACLANTCEN was requested to obtain clearance for Biodola Bay, Elba. The clearance was given for June 7 and onwards. Two and a half days of operations were completed in Biodola before conditions improved, and Alliance returned to Framura to resume scheduled operation June 10. The clearance for Biodola required all equipment and Alliance to be out of the bay by 1900 each day, which affected operations somewhat. Specifically, the acoustic navigation and communiucation network had to be redeployed every morning, and re-calibrated. However, the decision to go to Elba was the right one from MIT's point of view. Significant progress was made on both navigation and acoustic communication, as well as on dynamic control of Caribou with the 1x16-element nose array. During the last week in Framura, June 10-17, conditions were excellent and most of the objectives were met. During this entire period, the new BIB GPS tracking system was deployed as well, with the bouys acting as floats for the LBL navigation network.

Accomplishments

- *MOOS – Mission Oriented Operation Suite*

One of the main MIT objectives was the development of the fundamental control algorithms that allows fleets of AUVs to cooperate on adaptive sampling in the ocean environment. A key component of such algorithms is the capability of reacting to socalled 3rd party requests where a process external to the vehicle control, e.g. one running a sensor system or one running another AUV can request changes in behavior. These requests can arrive via the internal AUV Ethernet, or via acoustic modems. Native AUV software, including the one developed by Bluefin Robotics for the Odyssey III vehicle are in general developed for easy setup of survey patterns, e.g for side-scan imaging of a large area of seabed, and does not directly support 3rd party requests. Also, for safety and warranty reasons the commercial control software is in general based on a tightly closed architecture, the custumization of which is time consuming and expensive, requiring tight cooperation with the manufacturer. As a result, MIT decided in the fall of 2002 to develop a new, open AUV software architecture, MOOS – Mission Oriented Operating Suite with the following characteristics

- An alternative, small and fast source code solution for AUV operation
- Fully distributed, platform independent
- Mission Simulation, Playback and Reprocessing
- On the fly mission task arbitration and scheduling
- 3rd party task invocation - for example
    - via acoustic modem – mission start/stop - redirect
    - From scientific payload – "orbit this area" (if you can)
    - From another vehicle – 'my survey finished – come take photos"
- Remote control and "at sea" mission specification
- Start MOOS once – processes just "refresh" upon user changes. Very stable.

Since the first line of code was written by the developer, Dr. Paul Newman of MIT, in September 2001, MOOS has been implanted and tested on several different autonomous platforms, including an autonomous surface craft, and Odyssey II AUV, and two different land-robots. After delivery of the new Odyssey III, Caribou, to MIT in Dec. 2001, MOOS was integrated and underwent preliminary tests in late March, 2002 shortly before shipment to the Centre of all MIT equipment, and as a result, MOOS had only about 20 minutes of operation time on Caribou at the beginning of BP-02/MASAI-02. A significant part of the operation time during the experiment was therefore used on advancing the capabilities of MOOS to perform adaptive cooperative behaviors, including the following specific at-sea developments:Vehicle Control

-
    - Dynamic control of vehicle with SAS payload – interesting hydrodynamic properties
    - Execution of Survey's, Zamboni's, Tracklines, Waypoints
    - Pilot invoked "come home" facility and on surface remote control
- Navigation
    - Closed loop LBL/DVL/Compass navigation
    - Closed loop LBL net sharing for two AUV's using Xanthos and Caribou
- Acoustic Modem
    - Remote control of vehicle – mission start stop redirect
    - Active, unsolicited remote query of vehicle status – "tell me battery state" etc

- Broadcast of state – eg "current position is…" or "current task is….." etc
- Payloads
  - Integration and control of low-frequency SAS payload from other MOOS processes
  - Integration and control of Edgetech SSS/SBP payload.
- Missions
  - Over 500 complete mission executed. Many short (<2 min) but last days average mission time ~ 30 minutes.
  - Each mission was planned, executed and logged without a MOOS restart.
  - Very fast turn around: an ideal research platform

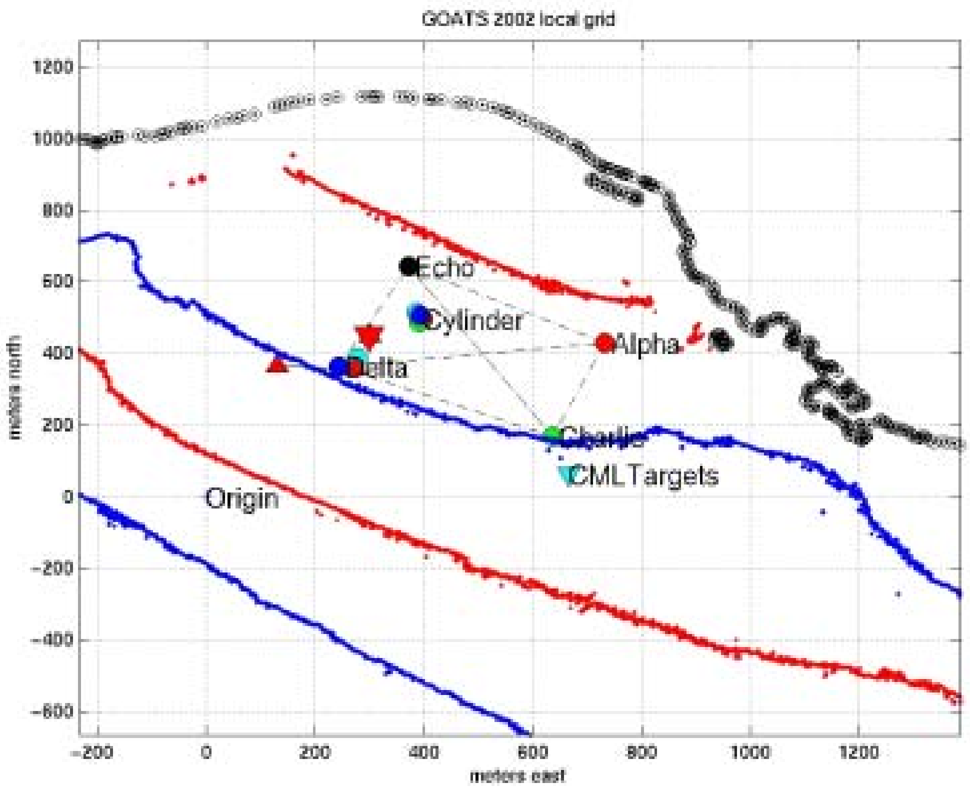

Figure 2. Framura test area with MIT LBL navigation and GIB tracking network.

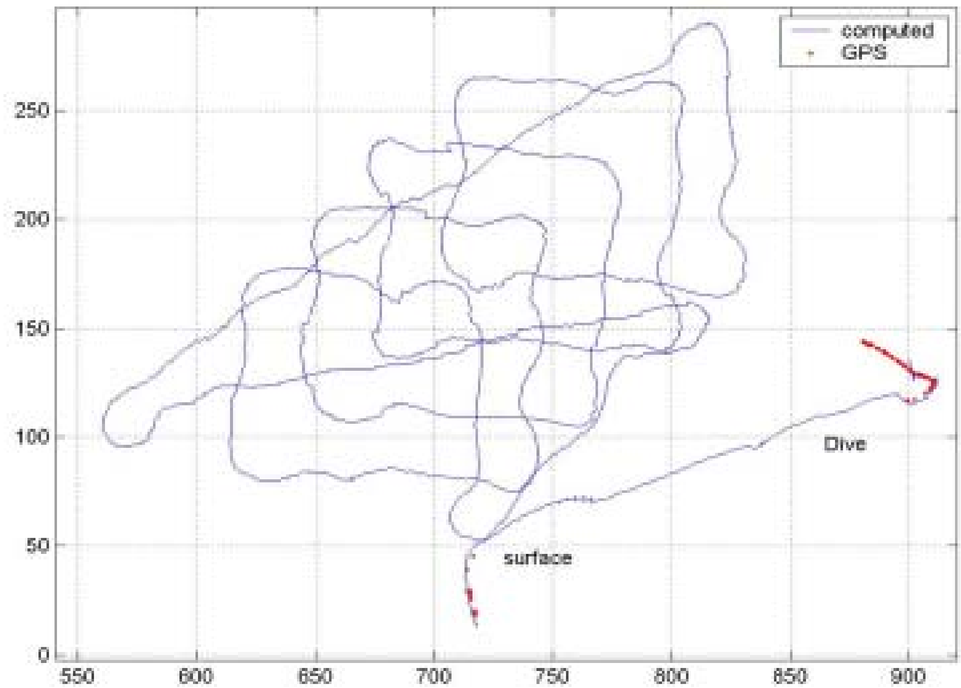

Figure 3: AUV navigation during SAS survey. Blue track indicates the onboard navigation result while the red dots indicate the GPS fixes while at the surface before the dive and after the surfacing, confirming navigation accuracy better than 1 meter throughout the mission.

- *Navigation*

One of the core components of MOOS is the navigation algorithm, fusing several independent navigation sensors into an optimal vehicle navigation involving multiple cooperating platforms. Caribou used an on-board DVL, compass, and GPS (while surfaced), together with a Sonardyne long-baseline acoustic navigation network, deployed in the Framura test area as shown in Fig. 2.
Fig. 3 shows a trajectory with a so called zamboni search pattern by Caribou in an area where many concrete blocks were observed in previous surveys as shown in Fig. 1. The vehicle was using the SBP source with the 2×8 nose array during the survey. The blue track indicates the vehicle navigation using all available sensors, fused by an extended Kalman filter, while the red dots indicate GPS fixes on the surface. The mission started at the easternmost point and ended at the southernmost point. As is obvious from the figure, the vehicle navigation achieved a position uncertainty at the end of the survey of less than one meter. This in spite of the fact that the LBL data were highly contaminated by false triggers generated by the low-frequency SAS system

- *Low-frequency SAS Sonar*

Another objective of the MIT effort was to test a new low-frequency SAS sonarusing the two arrays built by the Centre and mounted in the nose of Caribou. A dedicated acoustic acquistion systm has been developed by MIT and integrated in the Odyssey III as shown in Fig. 4

Figure 4. Low-frequency SAS sonar with nose-mounted 2x8 element array and acquisition payload with 4-20 kHz SBP source and 16-chanmnel DSP acquisition system.

The new SAS system developed at MIT has the following characteristics:

- 16 Array Input Channels, 100 KHz Sampling
- Simultaneous 16-Channel Sigma-Delta A/D Conversion
- Texas Instruments C6701 Floating-Point DSP
- Integrated 230 KHz D/A Converter
- 200-Watt, 4-24 KHz Acoustic Source
- Adjustable 20-70 Degrees from Horizontal in 5 Degree Increments
- 233 MHz Pentium Host CPU Board with Ethernet
- 30 GB Ultra DMA/100 Hard Disk for Real-Time Data Storage
- Time Tags Using GPS-Synchronized Rubidium Oscillator

The SAS sonar was integrated into Caribou and the MOOS software architecture before and during the cruise:

- Fully Integrated Odyssey-III Payload Section
    - Power and Ethernet Connectivity to Main Vehicle
- Full Software Integration with MOOS on Main Vehicle
    - Startup/Shutdown/Real-Time Status
    - MOOS-consistent file names
    - Real-Time Control of Sonar Parameters
        - Start/Stop Acquisition
        - Source Ping Rate
        - Sampling Period

    - Automatic Sharing of Real-Time Processed Data
        - Target Acquisitions/Tracking
- Adaptive Vehicle Control via Third-Party Requests
    - Real-Time Detection/Classification Algorithm on Host CPU

The new sonar system and its software integration was tested extensively during the cruise, with the results summarized as follows:

- Collected Sonar Data on Eight Separate Days
    - Approximately 20 GB of Data from 70 Missions
- No Significant Hardware Failures
- Proved Real-Time Mine Detection From an AUV is a Viable Concept
    - Successfully ran real-time, autonomous detection algorithm

Acoustics Modeling

In support of the analysis of the GOATS'98 and '2000 datasets, the OASES-3D target scattering and propagation model has been expanded to significantly. A new hybrid modeling component allows for proud or buried targets of arbitrary shape to be accurately modeled. This new capability provides thye first step towards the development of a high-fidelity model of the scattering from partially buried targets. As the previous target models, all environmental acoustic propagation effects from the source to the target and from the target to mono- or bi-static receivers is handled by OASES using the exact wavenumber representation under the assumption of latereal homogeneity of the environment. In the new component the target is represented by a virtual source approach where the target is replaced by a distribution of virtual sources the strengths of which are determined by satisfying a general arbitrary boundary conditions at the surface of the target. All that is required for the target is an impedance matrix relating the surface pressure to surface displacement, which may be determined by any method applicable to the specific target structure. Thus, for complex targets with structural elements, the impedance matrix may be computed using a finite element code. Since the impedance matrix is independent on the incident field it may be computed a-priori, and the scattered field for arbitrary, static or dynamic, sonar geometry may be computed very efficiently..

RESULTS

OASES-3D Modeling

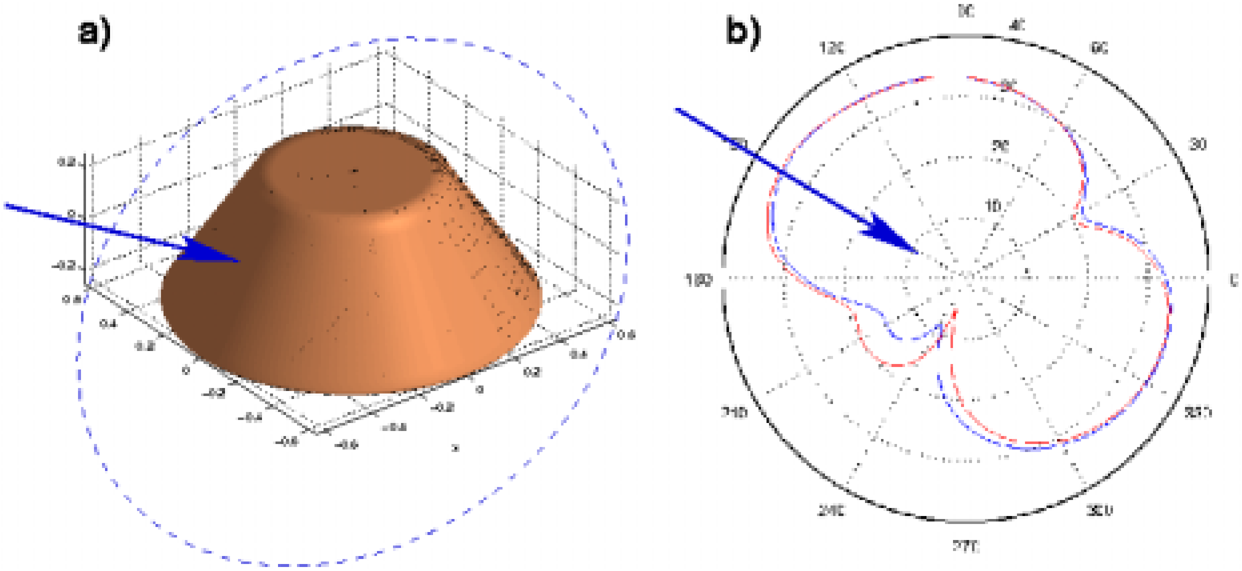

Figure 5: Benchmarking of new OASES-3D scattering model. (a) Scattering from trapezoidal, rigid target modeled using a virtual source approach and a finite element code (Burnett, SACLANTCEN). The in-plane scattered field is compared along a circle of radius 0.8 m. The incident field is a plane wave incident at 30 deg grazing angle (b) Scattered field computed by OASES virtual source model (red) and finite element code (blue).

The new virtual source scattering code integrated into the OASES-3D modeling framework ,[1,3-4] has been extensively tested and validated in FY02 by comparison to a finite element code developed by David Burnett and Mario Zamponi at SACLANT Undersea Research Centre. An example of the benchmarking results is shown in Fig. 5.

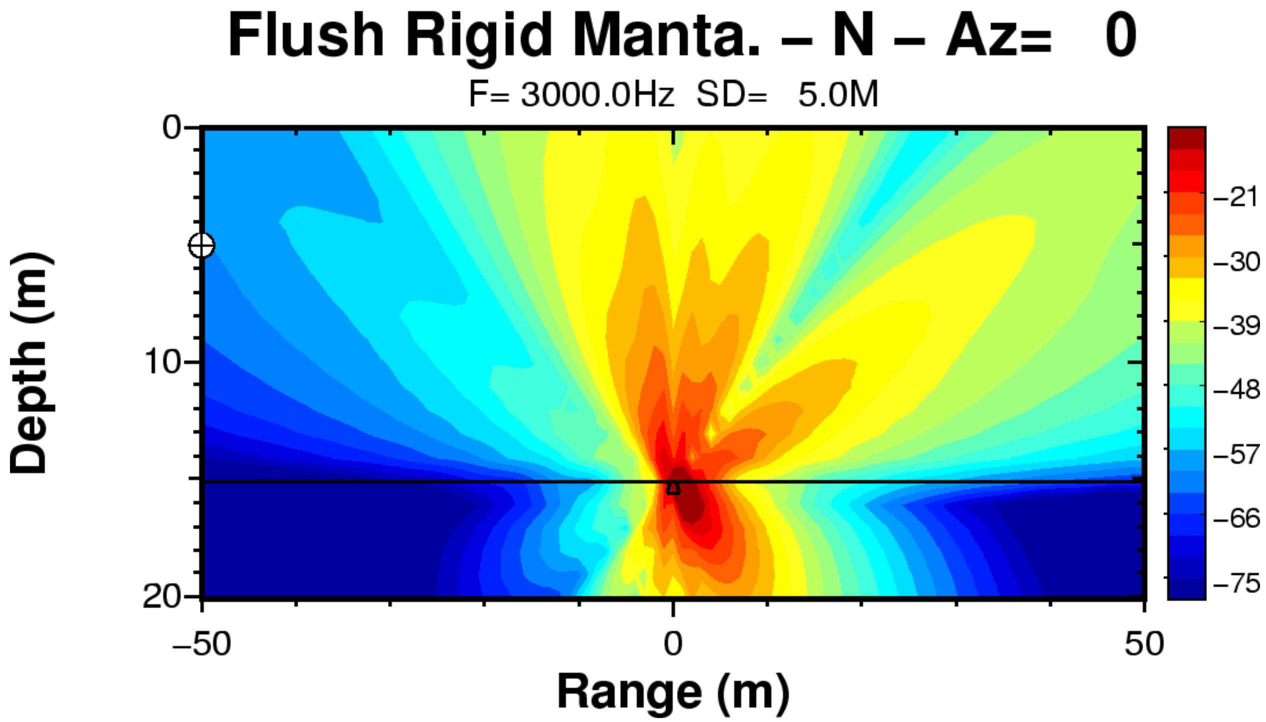

Figure 6. Scattered field pressure contours in dB for the rigid trapezoidal target shown in Fig. 5(a), flush buried in a sandy seabed. The target is insonified by a 3 kHz sonar beam iincident at a sub-critical 18 degrees from the left.

The main advantage of the hybrid scattering modeling framework of OASES-3D is the extremely efficient computation of the 3-dimensional scattered field throughout the stratified ocean environment once thye local scattering problem is solved for the particular incident field. Thus, for example, the scattered field produced by a flush-buried trapezoidal target in Fig. 6 is computed in a fraction of a second, and the field at any bi-static receiver position is therefore modeled with extreme efficiency. This particular result shows the dominance of the bistatic and forward scattering for this particular target shape, making it rather stealthy to mono-static sonar configurations, but potentially detectable by bi- and multi-static configurations such as provided by the GOATS concept.

Bistatic scattering from buried shells

The analysis of the extremely rich GOATS'98 dtataset is being continued to develop a better fundamental understanding of the scattering from buried targets insonified below the critical angle. Most recently this effort has concentrated on the analysis of the extensive dataset collected on a 128-element horizontal line array (HLA), suspended over the target area. A key component of theis analysis is the detection and identification of the various arrivals associated with the particular insonification and the elastic scattering process. Earlier analysis of this data suggested that existing scattering models, including those developed at MIT, were inadequate in modeling the observed responses, specifically the relative arrival times of the target multiples. However, the most recent analysis has shown that this discrepancy was associated with incorrect assumptions regarding the array location, and a resulting erroneous identification of the arrival structure. Resulting from the most recent analysis, Fig.7 shows the time and frequency dependence of backscattered field from a flush buried spherical shell, while Fig. 8 shows the traces of the strongest identifiable arrivals for a sequence of hydrophones in the HLA, providing the key to the identification.

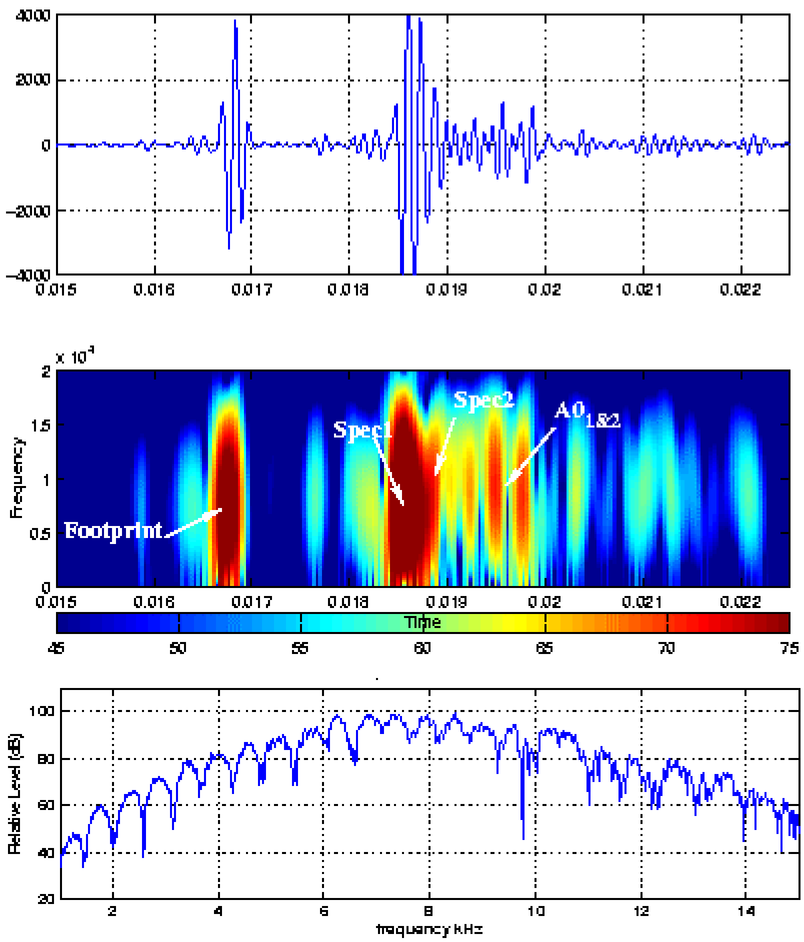

Figure 7: Time series, spectrogram , and a power spectrum of HLA receiver 44 positioned in the backscattering direction above a flush buried , sub-critically insonified target S2 .

The first arrival is associated with a close to perfect linear move-out with receiver range, consistent with his being the specular reflection off the seabed of the incident beam, here called the 'footprint' arrival. The second strong arrival 'Spec1' at 18.5 ms is the specular scattering by the target of the headwave generated in the sediment by the sub-critically incident beam, closely followed by another arrival 'Spec2' at 18.7 ms marking the specular scattering of the main incident beam, an interpretation supported by the observation that the time difference between these two arrivals in Fig. 8 is independent of the receiver range and bearing, identifying these arrivals being associated with two different paths of the incident field, i.e. the head-wave and the direct beam. A pair of elastic shell flexural returns A_{01} and A_{02} follow the two specular reflections separated from them by a couple of weaker S_0 compressional returns. It is also noticable that the initial arrivals have a peak frequency of at 8 Khz, consistent with the center frquency of the incident beam, while the A_0 returns peak at a higher 10 Khz. This supports the earlier hypothesis by Schmidt [4], that the subcritical excitation and radiation of the flexural waves on the buried shell assume the role of a filter modifying the frequency content of the scattered waves. Also, a distinct change in relative arrival time of the flexural arrivals can be observed towards the to of Fig. 8. This is consistent with the fact that these receivers are towards the backscattering direction, while the lower part of the plot correspond to sidewards scattering where the circumferential path of the shell waves is smaller.

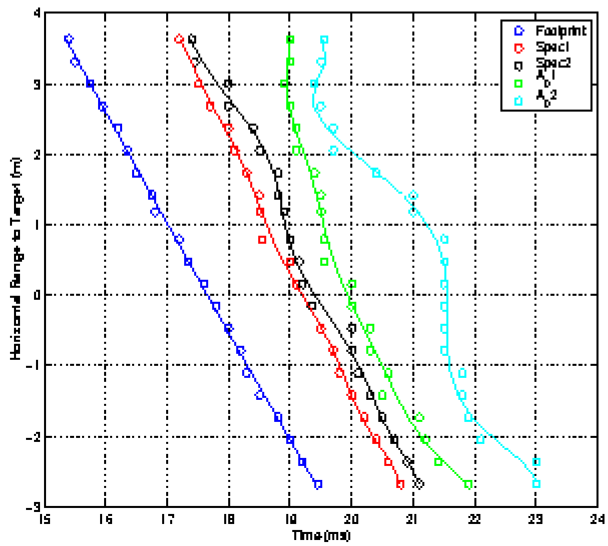

Figure 8: Horizontal range to target versus the time of arrival for the five arrivals along the HLA, receivers 14-94

IMPACT/APPLICATION

The long-term impact of this effort is the development of new sonar concepts for VSW MCM, which take optimum advantage of the mobility, autonomy and adaptiveness of the AOSN. For example, bi- and multi-static, low-frequency sonar configurations are being explored for buried mines in VSW, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment.

TRANSITIONS

The GOATS AUV effort has been and is conducted in cooperation with the MIT Sea Grant AUV Laboratory and Bluefin Robotics, a spin-off from the MIT Laboratory. Bluefin is currently developing and building the Odyssey III Battlefield Preparation AUV for ONR, and similar MCM platforms for the Coastal Systems Station (CSS) and QinetiQ (UK), building in part on the experience and results from the GOATS effort.

The results of th multi-vehicle navigation, communication and cooperative behavior is being transitioned into the Autonomous Operations Future Naval Capabilities (AOFNC) project

Demonstratio of Undersea, Autonomous Operation Capabilities and related Technology Development. John Leonard is the MIT PI of this joint project with Bluefin Robotics and the Naval Undersea Warfare Center..

The OASES acoustic propagation framework continues to be maintained and expanded. It is continuously being exported or downloaded from the OASES web site (http://acoustics.mit.edu/arctic0/henrik/www/oases.html), and used extensively by the community as a reference model for ocean seismo acoustics in general.

RELATED PROJECTS

This effort is part of the US component of the GOATS`2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre. The MIT GOATS effort is funded jointly by ONR codes 321OA (Simmen), 321OE (Swean), 321TS (Johnson), and 322OM (Curtin).

The GOATS effort is strongly related to the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00. Thus the GOATS'98 experimental effort was funded in part by the AOSN MURI, (PI: J. Bellingham). In terms of the fundamental seabed penetration physics there are strong relations to the High-Frequency Bottom Penetration DRI (PI: E. Thorsos). This effort also builds on acoustic modeling efforts initiated under the Sea-Ice Mechanics Initiative (SIMI), and continued under funding from ONR code 321OA (Simmen).

With its heavy focus on Synthetic Aperture Processing approaches and their extension to bi- and multistatic configurations in multipath SW VSW environments, there are strong relations to the ONR SASSAFRASS project (code 321TS and 321OA).

The OASES modeling framework being maintained and upgraded under this contract is being used intensively as part of the MIT AREA (Adaptive Rapid Environmental Assesment) component of the new ONR "Capturing Uncertainty" DRI (Grant # N0014-01-1-0817), aimed at mitigating the effect of sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assesment resources.

REFERENCES

1. Schmidt, H. "OASES V 2.7 User's Guide", Massachusetts Institute of Technology, 2000.

2. Schmidt, H., Maguer, A, Bovio, E., Fox, W.L.J., LePage, K., Pace, N.G., Hollett,R., Guerrini, P., Sletner, P.A., Michelozzi, E., Moran, B. and Grieve, R. "GOATS'98 – AUV Network Sonar Concepts for Shallow Water Mine Countermeasures," *SACLANT Undersea Research Centre*, Report SR-302, 1998.

3. Schmidt, H. and Lee, J.Y, "Physics of 3-D scattering from rippled seabeds and buried targets in shallow water," *Journal of the Acoustical Society of America*, 105(3), 1605-1617, 1999.

4. Schmidt, H. Three-dimensional scattering from buried targets in shallow water. *In*: Bovio, E., Schmidt, H., *editors*. GOATS 2000, SACLANTCEN CP-46, 2002Tesei, A., Lim, R., Maguer, A., Fox,

W.L.J., Schmidt, H. Measurements of acoustic scattering from partially and completely buried spherical shells. *Journal of the Acoustical Society of America* Submitted, 2001.

PUBLICATIONS

J. R. Edwards, H. Schmidt and K. LePage, Bistatic synthetic aperture target detection and imaging with an AUV, *IEEE Journal of Oceanic Engineering* 26(4): 690-699, 2001.

LePage, K., Schmidt, H. Bistatic synthetic aperture imaging of proud and buried targets using an AUV, *IEEE Journal of Oceanic Engineering* (In press), 2002.

LePage, K., Schmidt, H. Spectral integral representations of monostatic backscattering from threedimensional distributions of sediment volume inhomogeneities. *Journal of the Acoustical Society of America,* (In Press), 2002.

Tesei, A., Lim, R., Maguer, A., Fox, W.L.J., Schmidt, H. Measurements of acoustic scattering from partially and completely buried spherical shells. *Journal of the Acoustical Society of America* (In press), 2002.

Schmidt, H. Three-dimensional scattering from buried targets in shallow water. *In*: Bovio, E., Schmidt, H., *editors*. GOATS 2000, SACLANTCEN CP-46, 2002.

H. Schmidt and J.R. Edwards, GOATS: Multiplatform Sonar Concept for Coatsal Mine Countermeasures. In: A.C. Schultz and L.E. Parker editors: Multi-Robot Systems: From Swarms to Intelligent Automata. Kluwer Academic Publishers, 2002.

.J. J. Leonard, R. J. Rikoski, P. M. Newman, and M. Bosse. Mapping Partially Observable Features from Multiple Uncertain Vantage Points. To appear in *International Journal of Robotics Research.*

J. D. Tardos, J. Neira, P. M. Newman, and J. J. Leonard. Robust Mapping and Localization in Indoor Environments using Sonar Data. To appear in *International Journal of Robotics Research.*

M. Bosse, S. Teller, R. Rikoski, and J. Leonard. Omni-directional Structure from Motion Using Vanishing Points and 3D Lines. To Appear in *Visual Computer.*

Richard J. Rikoski, John J. Leonard, and Paul M. Newman. Stochastic Mapping Frameworks. Proceedings of the 2002 IEEE International Conference on Robotics and Automation, May, 2002.

John W. Fenwick, Paul M. Newman, and John J. Leonard. Cooperative Concurrent Mapping and Localization. Proceedings of the 2002 IEEE International Conference on Robotics and Automation, May, 2002.

Paul M. Newman, John J. Leonard, J. Neira and J. Tardos. Explore and Return: Experimental Validation of Real Time Concurrent Mapping and Localization. Proceedings of the 2002 IEEE International Conference on Robotics and Automation, May, 2002.

W. Xu, TC Liu, and H. Schmidt, "Beamforming based on spatial-wavelet decomposition," Proc. of the IEEE Sensor Array and Multichannel Signal Processing (SAM) Workshop, August, 2002.

T.C. Liu and H. Schmidt. "Auv-based subbottom target detection and tracking." OCEANS 2002: Reflections of the past, visions of the future, Biloxi, MS, 2002. MTS/IEEE.

T.C. Liu and H. Schmidt. "Concurrent detection and localization of buried targets using track-before-detect processing." 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2002. AIP.

J.R. Edwards and H.~Schmidt. "Real-time classification of buried targets with teams of unmanned vehicles." OCEANS 2002: Reflections of the past, visions of the future, Biloxi, MS, 2002. MTS/IEEE.

M. W. M. G. Dissanayake, P. M. Newman, H. F. Durrant-Whyte, S. Clark, and M. Csorba. *A solution to the simultaneous localization and map building (SLAM) problem,*
IEEE Transactions on Robotic and Automation, Vol 17, No 3, Pages 229-241, 2001

P. M. Newman and H. F. Durrant-Whyte. *An Efficient Solution to the SLAM Problem Using Geometric Projections*, Proceedings of the November 2001 SPIE conference, Boston, USA.

S. B. Williams, P. M. Newman, J. Rosenblatt, G. Dissanayake, and H. F. Durrant-Whyte. *"Autonomous Underwater Navigation and Control". Robotica,* vol 19, no 5, September, 2001 Pages 481-496.

J. J. Leonard, P. M. Newman, R. J. Rikoski, J. Neira, and J. D. Tardós. *Towards Robust Data Association and Feature Modeling for Concurrent Mapping and Localization*. Proceedings of the Tenth International Symposium on Robotics Research, Lorne, Victoria, Australia, November, 2001.

M. Stojanovic, L. Freitag, J. Leonard, P. Newman. *A network protocol for Multiple AUV Localization.* To appear in proceedings MTS/IEEE Oceans 2002 Conference, Biloxi, USA.